

# The cosmological evolution of the QSO luminosity density and of the star formation rate.

B. J. Boyle<sup>1</sup> and Roberto J. Terlevich<sup>2</sup>

<sup>1</sup> Anglo-Australian Telescope, PO Box 296, Epping, NSW 2121, Australia

<sup>2</sup> Royal Greenwich Observatory, Madingley Road, CB3 0EZ

## ABSTRACT

We demonstrate that the evolution of the QSO luminosity density with epoch displays a striking similarity to the cosmological evolution of the field galaxy star formation rate, recently derived from a number of independent surveys. The QSO luminosity density at 2800Å is approximately one-fortieth that implied by the star formation rate in galaxies throughout the past 11 Gigayears ( $z < 4$ ). This similarity suggests that a substantial fraction of the QSO luminosity may be closely linked to the star formation process and its evolution with cosmic time.

**Key words:** galaxies: active – galaxies: starburst – galaxies: galaxies: statistics – galaxies: quasars

## 1 INTRODUCTION

The recent results of Madau et al. (1996) and Connolly et al. (1997) relating to the cosmic evolution of the star formation rate (SFR) in galaxies have attracted much attention. A striking feature of these results is the rapid increase in the SFR over the range  $0 < z < 1.2$ , largely based on the CFRS sample (Lilly et al. 1996). Strong cosmological evolution has been a major feature of another extra-galactic population, QSOs, for almost 30 years (Schmidt 1968), with the most recent results (Boyle 1993, Hewett, Foltz & Chaffee 1993) demonstrating the existence of strong luminosity evolution in QSO optical luminosity function (LF) of the form  $L \propto (1+z)^3$  at  $z < 1.5$ . An equally notable feature of the galactic SFR evolution is the implied fall in the SFR at high redshifts ( $z > 3$ ). It is now also generally accepted that the space density of QSOs also declines at these redshifts (see Schmidt, Schneider & Gunn 1995, Warren, Hewett & Osmer 1994, Shaver et al. 1996). Thus the long-standing discovery of evolution in the QSO optical luminosity density would appear in many ways to track the more recently-discovered trends in the galaxy star formation rate. Indeed, Wall (1997) has found a striking similarity between the trend with redshift of the space density of flat-spectrum QSOs and the evolution of the SFR, and Dunlop (1997) finds that the evolution of the radio luminosity density of luminous radio sources is similar to the evolution of the UV luminosity density of star-forming galaxies.

These broad similarities between the galaxy SFR and the QSO evolution rate suggest that models which invoke a nuclear starburst as powering much of the QSO luminosity require closer attention. We have shown in a previous paper (Terlevich & Boyle 1993) that the observed LF of QSOs and its redshift evolution can be explained with a simple model

for the formation of the metal rich core of elliptical galaxies. In this model, most of the luminosity emitted by QSOs is caused by a nuclear starburst. Only 5 per cent of the total mass of the galaxy is involved in this nuclear starburst. The QSO phase represents about one fiftieth of the age of the Universe at  $z = 2$ .

This model is supported by spectroscopic studies of nuclear optical light in Seyfert nuclei that indicate the presence of luminous nuclear starbursts in nearby Seyfert 2 and some Seyfert 1 galaxies (Terlevich, Diaz & Terlevich 1990). Following this line, Cid Fernandes and Terlevich (1995) proposed that the featureless continuum in Seyfert 2 nuclei was produced by a nuclear starburst located in the dusty molecular torus and responsible for occulting from view the hidden Seyfert 1 nuclei.

Cid Fernandes and Terlevich's proposal has been confirmed by recent HST observations of nearby Seyfert 2 nuclei. Heckman et al. (1995, 1997) have demonstrated that all the continuum light in at least some Seyfert 2, all the ones observed so far, is due to a dusty nuclear starburst. Furthermore for at least the luminous Seyfert 2 Mk477, that is also seen as a Seyfert 1 in polarized light, the nuclear starburst is at least as luminous as the Seyfert 1 component. Thus an observer situated along the axis of the torus will detect comparable contributions to the optical continuum coming from the starburst and the Seyfert 1 or broad line region (BLR) component.

There is thus direct evidence that at least in some AGN a substantial part of the emitted optical luminosity originates in a nuclear starburst. How general can this effect be? One line of evidence comes from variability studies of QSOs. Some of these studies indicate that maybe up to 70 per cent of the optical/UV light emitted by QSOs is constant, i.e. does not vary and therefore can be in principle associated

with a nuclear starburst. Only about 30 per cent may be associated with the variable BLR (Cid Fernandes et al. 1996, Arétxaga et al. 1997).

In this paper, we now investigate the similarities between the redshift evolution of the galaxy blue luminosity density and that inferred for QSOs from the evolution of the QSO LF. Although broad similarities would not necessarily rule out models in which a supermassive black hole/accretion disk could provide much of the optical/UV luminosity (the amount of gas available to the black hole could be linked to the SFR), by far the simplest explanation of any similarities would be that the processes responsible for the evolution in the galaxy luminosity density were the same of those responsible for the evolution in the QSO luminosity density (i.e. star formation). For all the estimates we have adopted  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0.5$  and  $\lambda = 0$ .

## 2 QSO LUMINOSITY EVOLUTION

In order to compute the total QSO luminosity density as a function of redshift  $\rho_{LQ}(z)$ , we used the QSO luminosity function (LF) and evolution model of Boyle (1993) for  $z < 3$ . This incorporates strong evolution  $L \propto (1+z)^{3.4}$  at  $z < 1.9$ , and constant co-moving density thereafter,  $1.9 < z < 3$ . Alternative evolution models have been proposed for this redshift range (Hewett et al. 1993), incorporating a decline in the strong evolution at lower redshifts,  $z \sim 1.6$ , but continued slow evolution  $L \propto (1+z)^{1.5}$  until  $z = 3$ . The net effect of these two models is very similar, with the Hewett et al. (1993) smoothing out the transition from fast evolution at  $z < 1$  to slow or almost no evolution at  $z > 2$  (see Fig. 1). At  $z > 3$  we assume that the QSO LF falls in normalisation by a factor of 3 per unit redshift, in line with the density evolution model derived by Schmidt et al. (1993).

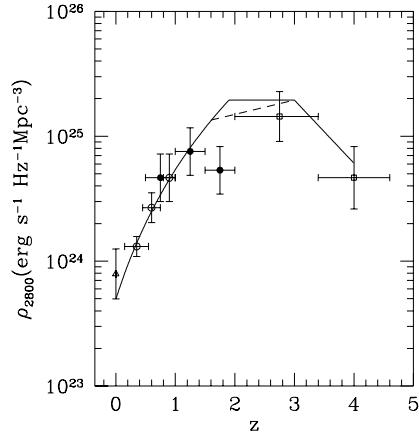
We calculated the QSO luminosity density at a fixed wavelength of 2800Å in the rest frame of the QSO. We adopted a spectral index of 0.5 to convert  $M_B$  magnitudes to monochromatic 2800Å luminosities. The expression for luminosity density is:

$$\rho_{LQ}(z) = \int_{L_{\min}(z)}^{L_{\max}(z)} L \Phi(L, z) dL$$

where the limits of integration  $L_{\min}(z)$  and  $L_{\max}(z)$  are the redshift-dependent limits of the luminosity function and were chosen to be  $0.01L^*$  and  $100 \times L^*$  respectively. The resulting relation is plotted in Fig. 1. In this figure we have also plotted the scaled luminosity density relation for galaxies compiled by Connolly et al. (1997), correcting the mass ejection rate back into luminosity density using:

$$\rho_{2800} = 2.8 \pm 0.3 \times 10^{29} \rho_z \quad \text{ergs}^{-1} \text{Hz}^{-1} \text{Mpc}^{-3}$$

The  $z = 2.75$  and  $z = 4.0$  points of Madau et al. (1996) in this compilation have been corrected for dust extinction following Pettini et al. (1997). The original values derived by Madau et al. (1996) for the high redshift SFR are a factor of 3 lower than the revised values plotted here. The correction for dust is highly dependent on the extinction law used. If the empirical law for starburst deduced by Calzetti, Kinney & Storchi-Bergmann (1994) were used, then the correction



**Figure 1.** Luminosity density – redshift relation for QSOs (solid line) based on the evolutionary models of Boyle (1993) for  $z < 3$  and Schmidt et al. (1995) for  $z > 3$ . The dashed line indicates the alternative evolution model of Hewett et al. (1993) for the redshift range  $1.6 < z < 3$ . The compilation of galaxy luminosity densities (scaled by 0.025) from Connolly et al. (1997) is also shown. Open circles: Lilly et al. (1996), Open squares: Madau et al. (1996), corrected for dust extinction by Pettini et al. (1997), open triangles Gallego et al. (1997); filled circles: Connolly et al. (1997).

factor for the Madau et al. (1996) values would be closer to 10–15 (Meurer et al. 1997). Finally, the values for the galaxy luminosity density were multiplied by 0.025 to normalise the relation to that derived for QSOs.

From this figure, it can be seen that all but one of the best-estimates of the redshift evolution of the SFR in galaxies are consistent with the redshift dependence of the QSO total luminosity density  $\rho_{LQ}(z)$ , but re-normalised by a factor 40.

This factor can be made consistent with the relative normalisation of the  $z = 0$  galaxy LF ( $4 \times 10^{-4} h_{50}^3 \text{ Mpc}^{-3}$ , Tammann, Yahil & Sandage 1979) and QSO LF ( $1.5 \times 10^{-6} h_{50}^3 \text{ Mpc}^{-3}$ , Boyle 1993) if the typical QSO ‘starburst’ luminosity corresponds to  $5\epsilon^{-1}L^*$ , where  $\epsilon$  is the fraction of the total QSO UV/optical luminosity due to the nuclear starburst. In the starburst model discussed above, it is likely that the majority of the emitted nuclear optical/UV light in all non-blazar QSOs is due to massive stars in a nuclear starburst, i.e.  $0.5 < \epsilon < 1.0$ , with the additional variable component or BLR, due either to accretion processes or to starburst-associated phenomena, representing less than half of the optical/near-UV light emitted by the QSO.

## 3 CONCLUSIONS

Despite the uncertainties with calibration of the different SFR estimates, all the information available indicates that there is an increase of about a factor of 10 in the SFR between the present epoch and  $z=1$ , consistent with that observed for QSOs. This corresponds to a redshift evolution in the mean luminosity ( $L^*$ ) of both galaxies and QSOs of the form  $L^* \propto (1+z)^3$ , which is also similar to the observed evolution in the infra-red luminosity of IRAS galaxies (Saunders et al. 1990), albeit over a much lower redshift range ( $z < 0.1$ ). Even at redshifts higher than  $z=1$ , where

the uncertainties are larger, the agreement between the QSO and galaxy samples, both in the location of the maximum and the high redshift decay rate is remarkable.

This result is consistent with our earlier finding (Terlevich & Boyle 1993) that the observed LF of QSOs and its redshift evolution can be explained with a starburst model for the formation of the cores of elliptical galaxies at high redshift.

All this strongly suggests that the mechanism responsible for producing a dominant fraction of the UV/optical QSO luminosity is closely linked to processes of star formation and galaxy formation and evolution. The simplest conclusion is that a substantial fraction of the emitted luminosity in the optical/UV spectrum of QSOs is indeed associated with a nuclear starburst.

It remains to be determined whether the signatures of a young stellar population are present in the UV/optical spectra of high redshift QSOs, as seems to be the case in nearby type 2 Seyferts.

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